Safety Design Criteria for Explosives Manufacturing and Storage Facilities

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Abstract

The Picatinny Arsenal Safety Design Criteria Program is aimed at establishment of quantitative, realistic criteria for optimum design of protective structures to prevent propagation of explosion, injury to personnel, and damage of materiel.

The overall program consists of three phases. Phase I deals with prevention of propagation and personnel injury due to pure blast effects. Phase II deals with the effects of primary fragment impacts resulting from rupture of the donor explosive casing in causing explosion propagation. Phase III deals with the development of design criteria for barricades and substantial dividing walls for prevention of explosion propagation and personnel injury.

Phases I and II of this study cover establishment of quantitative design criteria for explosives facilities relating to prevention of explosion propagation by blast and fragment impact effects. The methods presented are based on prediction of large-scale behavior of these materials employing relationships which require data from small scale tests only. Relationships have also been developed which permit the calculation of safe distances for prevention of propagation of detonation due to fragment impact between adjacent potentially mass detonating explosive systems, for any assumed degree of risk and degree of steel casing. These relationships permit prediction of probability of propagation in an existing situation as well as calculation of necessary changes in acceptor shielding and/or separation distances for any other tolerable degree of risk.

Phase III of the program, deals with quantitative methods for realistic design of protective walls or combinations of walls (manufacturing bay or storage cubicle). Consideration is given to such factors as donor effects, wall responses, and acceptor (personnel, equipment or another explosive charge) sensitivity to the effects of donor detonation. Special emphasis is placed on close-in effects of donor detonation where non-uniformity of wall loading makes the application of the plane wave theory not valid. The donor charge which determines the blast loads and primary fragments is discussed in terms of various parameters of donor characteristics. Wall responses (to the blast loads resulting from the donor explosion) are discussed in terms of various modes of wall failure which may impair structural integrity of the wall. These are: (1) spalling (causing formation of secondary fragments) (2) punching (local shear failure causing formation of secondary fragments) (3) flexural failure (caused by overall flexing action of the wall which brings the wall to the point of incipient breakup) (4) total destruction of the wall

(causing complete breakup into secondary fragments) (5) penetration of the wall by primary missiles (resulting in either perforation of the wall or spalling). Also discussed are various degrees of wall support as well as different types of wall construction including sandwich-type walls.

The acceptor sensitivity is discussed in terms of either total protection level (for personnel and equipment) where essentially no damage to a protective wall can be tolerated, or lesser degrees of protection to protect against propagation of explosion.

Introduction

The lack of quantitative design techniques for safe explosives storage and manufacturing facilities has been a continuing problem. Although present safety regulations have been effective in preventing explosion propagation over the past years, this has been largely due to the high degree of overdesign incorporated in these regulations. Moreover it has become increasingly apparent in recent years, particularly with the advent of high energy propellants, that the present safety regulations are seriously inadequate in that they do not provide systematic techniques for optimum design of protective structures required in explosive and propellant manufacturing plants and storage areas. The aim of the Picatinny program is to establish such quantitative realistic design criteria which can be used with confidence in engineering protective structures to prevent propagation of explosions, injury to personnel, and damage to materiel.

The various phases of the program are shown schematically on Figure 1 which shows phases completed and those in progress at the present time. Phase I of the overall program deals with propagation of detonation due to pure blast effects (sympathetic detonation). Phase II deals with the effects of primary fragment impact (resulting from rupture of the donor explosive casing) in causing explosion propagation. Phase III deals with the development of design criteria for protective structures for prevention of explosion propagation and personnel injury.

The analytical portions of the overall program have been essentially completed. Detailed results of these studies are contained in References 1, 2, 3, and 4.

At present a model scale test program is in progress which is designed to confirm the design relationships developed, and/or to indicate areas where these relationships should be modified or supplemented.

Phase I - Sympathetic Detonation

This phase of the program deals with establishment of realistic quantity-distance relationships for prevention of sympathetic detonation. The general equation proposed is shown in Figure 2 and is based on correlation of available data and relationships reported by various investigators. It has been found to hold fairly well for donor charges of various explosives ranging from 1-250,000 pounds of weight. This equation accounts for various factors in addition to weight (i.e. degree of confinement, ground reflection, explosive composition, and shape) which affect the peak pressure blast output of a donor charge. This is accomplished by means of the various coefficients indicated which refer the actual donor charge weights to a set of standard conditions. The factor K, therefore, is a constant for each explosive depending only on its sensitivity to blast (i.e. considering the explosive in the role of acceptor charge). Each K value corresponds to a particular peak pressure which is the minimum blast pressure required to cause sympathetic detonation. It should be noted at this point that the cube root law correlation and the method of donor weight adjustment employed are consistent with the assumption of peak pressure as the criterion of explosive blast output. The factor K for a particular material can be determined by a series of small scale tests in which different weights (e.g. 1-100 pounds) of bare spherical TNT charges held sufficiently high above the ground so that ground reflections may be considered negligible (i.e. F_c, F_s, F_e, and F_r each equal 1) are detonated at varying distances from an acceptor charge of the material in question. A logarithmic plot of the maximum distance at which sympathetic detonation occurs versus corresponding donor weight should give a straight line of 1/3 slope, the intercept of which on the distance axis is equal to K. Concerning the donor weight adjustment factors, a considerable amount of information relative to these factors is available in the literature (References 5 and 6). In cases where coefficients must be determined this can be accomplished by appropriate small scale tests. For example, the composition coefficient F_e, for a new mass-detonating explosive could be determined by the method outlined on Figure 3.

Figure 4 is a simplified illustration of what can be done with the proposed quantity-distance relationship for sympathetic detonation. First, it shows a logarithmic plot of the available test data relative to occurrence of sympathetic detonation. The effective donor weights ranging from 3-450,000 pounds were calculated by adjusting the actual donor weights (1-250,000 pounds) by the method previously described. The plotted distance corresponding to any indicated charge weight approaches the maximum distance at which sympathetic detonation would occur with that charge; or conversely the plotted donor charge weight corresponding to any indicated distance approaches the minimum weight necessary to produce sympathetic detonation at that distance. As would be expected, the plot shows a region in the weight-distance plane where sympathetic detonation did not occur. A straight line drawn to separate the region of non-occurrence of sympathetic detonation from the region where sympathetic detonation did occur, has a slope of approximately 1/3 and corresponds to the equation $d_m = 3.1W_e^{1/3}$ and a peak pressure of 100 psi. This is a gross separation based on the most sensitive explosive considered, i.e. dynamite. Of course, the methods previously described could be used to establish a family of such lines, one for each mass detonating explosive depending on its sensitivity. For many explosive materials of current military interest, such lines will lie considerably below the gross boundary shown on Figure 4. (i.e. they will be less sensitive). Indeed, for TNT-base explosives, threshold peak pressures required for sympathetic detonation are of the order of several thousand psi. The line shown immediately above the sympathetic detonation boundary corresponds to a pressure of 30 psi and has the equation $d_s = 5W_e^{1/3}$ which constitutes the application of safety factor of 1.6. It is apparent that present intraline and magazine quantity-distances for mass-detonating explosives (broken lines on Figure 4) are overly conservative for prevention of propagation due to pure blast effects. It should be noted that, although a literal interpretation of these regulations is that they are for prevention of pure blast effects only, they are intended to provide some degree of protection against propagation by fragment impact, since a real situation where only blast effects are significant is unlikely. The extent of this protection against fragment effects, however, is not quantitatively defined. As will be discussed later in this paper, Phase II of the Picatinny program is concerned with a quantitative approach to quantity-distances for fragment effects.

The significance of factors affecting the output of a donor charge is shown in Figure 5 which is a summary of calculations made by the method previously described to arrive at effective weights of a 10,000 pound donor charge detonated under a wide range of conditions, and corresponding safe distances obtained from the $d_s = 5W_e^{1/3}$ quantity-distance relationship. We have assumed a cylindrical shape for the charge, corresponding to a shape correction factor (F_s) of 1.25. As indicated at the left of the table various explosive compositions were considered, corresponding to composition correction factors (F_e) ranging from 1.0 for TNT to 1.27 for explosive Z. Across the top of the table are assumed correction factors (F_r) ranging from 1.5 to 2.0 for various degrees of ground reflection, and for each of these reflection conditions, correction factors (F_c) ranging from 0.8 to 1.17 for various degrees of confinement are indicated. The calculated values of effective donor charge weights range from 12,500 pounds to 40,000 pounds with corresponding safe distances of 116 feet and 172 feet, respectively. According to present intraline regulations, the explosive weight would be taken as 10,000 pounds and the corresponding safe distance as 400 feet, regardless of the widely varying conditions indicated.

Phase II - Propagation by Primary Fragments

This phase deals with the effects of fragment impact in causing high order detonation in an explosive charge, and related safety design criteria. This work has resulted in the establishment of (1) a method of predicting the vulnerability to high order detonation of an explosive system (or vulnerability to mass detonation of adjacent explosive systems) in terms of geometry of the system (e.g. explosive weight/casing rate, casing thickness and diameter) and explosive properties (e.g. output and sensitivity), and (2) a method for calculating safe distances for any assumed degree of risk. The methods are based on correlation of various relationships developed by British and U. S. investigators as a result of theoretical studies, confirmatory tests, and actual experience. The general relationships are presented schematically on Figure 6. These equations permit prediction of the gross mass-detonability characteristics of explosive systems. Shown are the factors which must be considered for any explosive system in either a donor or acceptor role. As indicated by equation (1) an output constant (E') must be established for the donor charge. Values for several standard explosives are available in the literature, Reference 7. For other explosives or propellants, E' could be established experimentally by conducting small scale tests in which cased samples of various E/C ratios are detonated and corresponding fragment velocities measured. The output constant is readily obtainable from a plot of (V_o) vs (E/C) in accordance with equation (1). Equation (2) is for calculation of the number of fragments in any particular weight range produced by detonation of a cased charge. A special case of equation (2) can be used to calculate the mass of the largest fragment (m_{max}) produced in the detonation according to equation (2a).

Considering, now, an explosive system in the role of an acceptor, equation (3) indicates that an explosive sensitivity constant (K_f) must be established for the acceptor explosive. As in cases of the other constants previously discussed, values of this constant are available for some of the well known explosives such as TNT and RDX/TNT mixtures (Reference 8). For other explosives and mass-detonating propellants the (K_f) value could be established by a plot of V_b vs $f(t_a)(m)$ in accordance with equation (3). A simple method of obtaining the necessary data would be to fire individual fragments of known mass against explosive charges with various degrees of casing, and determining, for each charge, the minimum velocity of a given fragment required to produce high order detonation.

Once the various explosive constants have been established, and knowing the overall geometry and dimensions of an explosive system, it can be seen from Figure 6 that a reasonably reliable prediction as to its vulnerability to high order detonation by fragment impact (or its potential ability to contribute to propagation of an explosion, when considered in relation to any specific environment of adjacent explosive systems) can be made by a straightforward series of calculations. Thus, for a particular donor-acceptor situation (V_o) and (m_{max}) are first calculated. Since the equations are based on the assumption of cylindrical cased charges (i.e. constant cross-section) this will often require consideration of the donor in sections in such a way that equivalent cylinders can be constructed, having average wall thickness, average charge diameter, and the same (E/C) ratio as the actual section. After calculating (V_o) and (m_{max}) for each section the corresponding value of (V_{bmin}), is calculated, assuming impact at the thinnest portion of the acceptor casing (i.e. the most severe conditions). It is also assumed that the acceptor is in very close proximity to the donor (again, the most severe condition) so that fragments strike the acceptor at their maximum velocity (V_o), i.e. there are no velocity losses which would increase with increasing distance from the donor. As shown in Figure 6, therefore, the ratio (V_o/V_{bmin}) is a criterion for predicting the gross mass-detonability characteristics of explosive systems.

Development of relationships for calculation of safe distances in terms of probability of high order detonation occurrence or risk of propagation of detonation by fragment impact at these distances will now be discussed. For the sake of simplicity and convenience a graphical representation of these relationships is shown schematically in the next series of figures.

The plot presented on Figure 7 is based on equation (4). It relates fragment striking velocity (V_s) with fragment mass (m) at any distance from the detonation source (d) (constant distance lines - d_m being limiting distance at which detonation will occur). Each plot is made for a single value of initial velocity of donor fragments (V_o). A series of plots like the one presented on Figure 7 can be prepared for different values of (V_o). The constant (k) is a function of the presented area to fragment mass ratio, density of air, and air drag coefficient. (References 7 and 9). Figure 8 is a schematic representation of equation (3) which defines the minimum velocity a fragment must have in order to detonate a given acceptor. This plot relates the boundary velocity (minimum striking velocity at which a high order detonation will occur) with fragment mass (m) and acceptor casing thickness (t_a) and/or thickness of shielding in front of acceptor charge. The graph is plotted for a single explosive sensitivity (expressed in terms of the sensitivity constant (K_f), discussed previously).

When the plots from Figures 7 and 8 are combined as shown on Figure 9 useful relationships are obtained. Figure 9 relates striking velocity (or boundary velocity) of a fragment with fragment mass at various distances (d) and acceptor casing thickness (t_a). If boundary velocity of a fragment is now equated to its striking velocity, it becomes possible to find the minimum effective mass of a fragment produced by the donor explosive that will cause a high order detonation in the acceptor charge at any distance from the donor (d) and/or shielding of the acceptor (t). The number of such effective fragments produced at any distance from the donor charge can then be calculated from equation (2).

It is of interest to note the limiting case which is shown by equation (4a) on Figure 9. This indicates the maximum distance (d_m) at which propagation by fragment impact can occur for a given donor - acceptor situation. This is the distance at which the largest fragment (m_{max}) produced by the donor strikes the acceptor at the minimum velocity ($V_{b_{min}}$) required for detonation. It should be noted further that in terms of probability of acceptor detonation this is a boundary situation representing minimum probability of acceptor detonation occurrence, i.e. maximum distance, minimum boundary velocity, and minimum number of effective fragments. (the single largest donor fragment). At greater distances and/or lower velocities, the probability of acceptor detonation is, therefore, presumed to be zero.

The general case of reducing design distances from the limiting distance value (as expressed by equation (4a)) and/or shielding thickness by accepting a certain risk or probability of the possibility of high order detonation occurrence will now be considered. The probable number of effective hits (i.e. hits which upon striking the acceptor charge will cause high order detonation) by impacting fragments is expressed by equations (5) and (5a), Figure 10 (Reference 7). As can be seen from this equation, the probability per unit area is proportional to the number of effective fragments (N_x) (obtained from equation (2) previously discussed) and inversely proportional to the distance between the donor and acceptor charges. Included in the equation is a constant (g) governing the distribution of fragments, which depends on the spacial angular distribution of fragments. The plot shown on Figure 10 relates the distance between the donor and acceptor charges (d), shielding (t_a), and probability of high order detonation occurrence (E). The zero probability curve (P_o) indicates a relationship between the distance (d) and shielding (t) beyond which no high order detonation is possible. This line represents the limiting case mentioned earlier.

The higher the probability level that can be tolerated, the lower the distance-shielding combination necessary. This relationship permits gross prediction of the necessary separation and/or shielding between two explosive systems at any degree of probability of high order detonation occurrence. To compose such a relationship for a specific situation all that would be necessary is knowledge of the geometry of the system and the previously discussed explosive properties relating to sensitivity and output.

Phase III - Design of Protective Structures

The design or capacity of a protective wall or combination of walls (a manufacturing bay or storage cubicle) must be determined when considering any explosive manufacturing and/or storage situation. Although current regulations give guide lines for establishing barricades and substantial dividing walls which have been effective for many years, a quantitative procedure for assessing the degree of protection which may be expected from existing protective walls, or designing new walls is not available.

Developing protective wall design criteria (based on existing data and theoretical consideration) has been primarily concerned with relatively distant effects of explosions where a plane wave approach may be employed. Although situations of this sort are of occasional interest in Ordnance, the majority of cases are concerned with close-in effects where explosives are in relatively close proximity to the protective wall. Application of plane wave theory is not valid in such cases because of non-uniformity of wall loading (Reference 4).

A typical situation for which structural design criteria must be considered consists of three separate but related systems as presented on Figure 11, i.e. the donor (explosive material) which produces the damaging output, the acceptor (explosives, equipment, personnel) which will regulate the allowable tolerances of the overall system, and the intervening protective barricades, walls and/or distances which reduce the donor output to a tolerable level with respect to the acceptor.

Donor Effects

The damaging output of the donor is in the form of blast pressures and/or primary fragments, depending upon whether the explosive is cased or uncased. Based upon maintaining the overall stability of a protective wall, the blast pressures and impulse loads resulting from the detonation will be of prime importance (References 10 and 11). The physical properties of the donor system will determine the magnitude of the blast loads and the distribution of the pressure pattern on the wall, as well as the mass-velocity characteristics of primary fragments. These properties consist of (1) explosive characteristics, namely, type of explosive material and energy output, weight of explosive, and type and thickness of casing, (2) location of the explosive relative to the barrier and/or acceptor, (3) magnification and reinforcement of the initial blast wave by the presence of adjacent obstructions and/or structures.

Three basic donor charge locations are of interest as shown on Figure 12. First, the donor may be in free air with the blast wave propagating out from the center of the explosion and striking the wall (Figure 12a). Secondly, the donor may be at such a location relative to the wall that a Mach stem will be formed which only partly envelopes the wall, while the remainder of the wall is subjected to free air pressures (Figure 12b). Third, the charge location may be such that the pressure in the Mach front will be felt over the entire wall surface. The wall is then subjected to a uniform blast load or plane wave (Figure 12c). Further details are given in Appendix A.

In considering any particular wall of a cubicle type structure the blast enhancement effects due to reflections from the ground and adjacent walls must be considered. This is done by determining applicable reflection coefficients, which in turn are used to determine the equivalent weight of the charge acting on the wall.

Figure 13 indicates graphically the method for determining reflection factors as a function of various parameters. These reflection factors are utilized as multiplying factors to be applied to the actual charge weight, thus obtaining an equivalent charge weight (see Appendix B).

Wall Responses

The response of the protective structure to donor output will depend on the properties of the donor system as described above and the physical characteristics (material, strength, and configuration) of the structure itself. The donor output will establish the loading on the wall while the wall characteristics will govern its restraining capabilities to the applied load. When a protective wall is subjected to the detonation effects of an explosion, the wall will either remain intact (elastic response) undergo plastic action (permanent deformation) or fail, depending on magnitude of the load, load distribution, and the wall response. (Reference 12). For close-in detonations, design for elastic response of a wall will be practical only for small charges and generally is only of concern in the design for protection of personnel and/or valuable equipment. For those systems where the integrity of the wall is not essential, the wall response may be expressed in terms of various modes of failure. A schematic representation of these failure modes is shown in Figure 14. The wall can be affected either by primary fragments or by blast. Primary fragments can either perforate the wall and come out on the acceptor side with some residual velocity, be embedded in the wall resulting in spalling, or be embedded in the wall without causing any damage on the acceptor side (indicated by "no action" on the chart). Spalling caused by primary fragments produces secondary (concrete) fragments of extremely low velocity (several feet/sec.). In most cases (except where personnel protection is involved) these effects can be neglected. On the other hand perforation of the protective wall by primary fragments may cause propagation in the acceptor charge if their mass and residual velocity are sufficiently high. A quantitative method has been developed for estimating residual velocity of primary fragments as a function of wall thickness, fragment size and material, and initial fragment velocity. (See Appendix C).

Response of the wall to blast effects of close-in detonation may be expressed in terms of several modes of wall failure (shown on the chart). Under the action of a blast load, these modes consist of (1) the formation of concrete fragments, (secondary fragments) by scabbing (spalling) action of the rear surface of the wall (2) local failure of the wall resulting from development of excessive local shear stresses (punching failure), (3) flexural failure of the wall due to the overall bending action of the structure (including shearing at the base), and (4) total destruction resulting in collapse of the wall due to the combined action of several of the previously mentioned failure modes. Figure 15 is a plot relating mass, velocity and kinetic energy with charge weight and distance from the wall for the spalling mode of wall failure. Figure 16 is a similar plot indicating the mass, velocity and kinetic energy of the punched out section of the wall as a function of donor charge weight and distance from the wall. When total protection is required, such as for personnel or very specialized equipment, neither punching nor spalling can be tolerated. Figure 17 relating charge weight with scaled distance indicates threshold conditions of non-occurrence of spalling for various wall thicknesses. For a given charge, spalling failure will generally occur at threshold scaled distances greater than that required to produce punching. This chart, therefore, also serves as a conservative criterion for determining the occurrence or non-occurrence of punching.

The flexural mode of failure involves failure due to overall bending action and/or shearing of the wall at its base produced by the blast load impinging on the wall surface. The wall bends and deflects until such time as the entire system comes to rest at some permanent distorted position or collapse occurs at an overstressed section of the wall. The occurrence of the final permanent distorted position or failure will depend upon the magnitude of the applied load and the load carrying properties of the wall such as its moment and shear capacities. Figure 18 represents incipient conditions of flexural failure for a cantilever wall. The charge weight is correlated with the wall height for various wall resistance requirements expressed in terms of moment capacities (determined by concrete strength, reinforcement and wall thickness). For any point on the line of constant pressure leakage (blast leakage over and around the wall) relating minimum wall height with donor charge weight, the intersection with a constant resistance line indicates the flexural failure threshold condition for the wall. For total protection the wall capacity must be greater than that for incipient failure conditions indicated on the chart. On the other hand, when protection against explosion propagation is the only requirement, wall collapse is tolerable as long as the secondary fragments do not become a new source of propagation of the acceptor charge.

The total destruction mode of failure will now be considered. Figure 19 is a plot for determining velocity and kinetic energy which will be produced by the failure of a wall due to punching, flexural failure, or a combination of both as a function of donor charge weight, for various secondary fragment masses. Each chart is for a particular wall thickness and scaled distance. The mass distribution of these fragments will depend upon such factors as charge size and location, wall configuration (height thickness, reinforcement, support conditions) and the properties of the concrete, while the fragment velocity will be governed by the fragment mass and the magnitude of the impulse load acting on this mass after wall break-up. The properties of reinforced concrete cannot be completely defined due to its non-homogeneous nature, and therefore the velocity of the various fragments cannot be precisely predicted for a given condition. However, an estimate can be made of the average value of the maximum velocity of any particular size fragment formed upon collapse of the wall. The chart presented in Figure 19 is based on such estimates.

This paper, thus far, has dealt with standard reinforced concrete cantilever walls. Charts similar to those shown have been developed for walls with two adjacent fixed edges and two free edges, walls with three fixed edges and a free top edge, walls fixed on all four edges and one way spanning walls restrained on both edges. Also, in addition to the standard reinforced concrete wall, two other types of wall construction have been considered, namely, a standard reinforced concrete wall with stirrups added primarily to increase resistance to punching, and a sandwich wall (two concrete walls with sand fill between them). Further details on the sandwich-type construction are given in Appendix D.

Acceptor Response

The acceptor regulates the tolerances for which an overall system is designed. Here the yield and location of the donor along with the capacity of the protective structure must be selected to produce a balanced system with respect to acceptor sensitivity. The acceptor may consist of either another explosive charge, personnel and/or valuable equipment. In case of personnel and equipment, full protection will usually be required. For explosive acceptors the degree of protection required for prevention of propagation will usually be less than that required for total protection, and will generally, be governed by the detonability of the acceptor when subjected to (1) blast effects developed by detonation of the donor explosive, (2) primary fragment impact, and (3) secondary fragment impact resulting from break-up of the wall. Based on limited data available from initial tests conducted under one phase of the confirmatory test program mentioned early in this paper, impact of secondary fragments appears to be the most probable cause for detonation of the acceptor charge. No conclusive experimental data are available thus far for complete quantitative evaluation of secondary fragment parameters (mass, velocity, shape etc.) and their relation to occurrence of detonation in the acceptor charge. As the test program progresses, these relationships will be established.

In conclusion, it is expected that the Safety Design Criteria program will result in far reaching and continuing benefits to defense agencies as well as private industry engaged in manufacture of explosives and high energy propellants with respect to permitting most effective use of existing explosives storage and manufacturing facilities, and optimization of construction of new facilities.

APPENDIX A

Blast Loads on Walls Subjected to Combined Free Air and Reflected Pressures and Walls Subjected to Plane Wave

When an explosion occurs near a dividing wall such that a Mach stem is formed, partly enveloping the wall, the structure is subjected to both free air and reflected pressures.

As the incident shock wave expands radially from the center of the detonation, the shock front will come in contact with one or more reflecting surfaces. These surfaces are the wall in question and adjacent members of the structure (walls, floor, etc.) If a portion of the wall in question is subjected to the shock wave front before the frontal pressures have been magnified by the wave impinging on adjacent members, this section of the wall is considered to be subjected to free air pressure only. On the other hand, if the pressures acting on a portion of the wall have been intensified by the presence of one or more adjacent members, then this section of the wall experiences reflected pressures. The demarcation between the two loading conditions is defined by height of the triple point (point at which incident shock, reflected shock, and Mach fronts meet), ground zero distance (measured along the reflecting surface from a point normal to the explosion to the point in question) and the height of explosion above the reflecting surface. (See Figure A1).

When a wall is subjected to a plane shock front traveling normal to the wall, every point on the front surface of the wall may be assumed to be subjected to the same shock overpressure at any particular time after the arrival of the blast wave at the wall. Therefore the reflected (face-on) pressures, resulting from the shock front impinging on the wall, will be uniform over the entire wall surface.

Whether a wall is subjected to a plane shock front may be determined by the path of the triple point. If the height of the triple point is greater than the height of the wall, when the shock wave arrives at the wall, the wall is subjected to uniform pressures or a plane shock wave (Figure A2).

APPENDIX B

Calculation of Blast Loads Acting On Protective Walls of Cubicle Type Structures

To analyze the effects of close-in detonation within a cubicle type structure, the actual loading conditions can be approximated by determining the reflection factor (R_I) based on the positive free air impulse loading. The reflection factor, is defined as the ratio of the yield of an explosion in free air to the yield of an explosion near a reflecting surface, each of which produce equal total impulse loads and therefore relates the magnified value of the free air positive pressure impulse acting on a wall, due to the surrounding structure, to the total impulse of the blast loading (positive phase of both free air and reflected pressures) acting on a wall. For the utilization of the reflection factor, the type of wall (boundary conditions) and the location of the charge in relation to the wall and the surrounding structure must be known. For cubicle type structures where the walls are generally supported on two and/or three sides (Figure 11)(one side and top open to the atmosphere), the reflection factors are related to the normal scaled distance (Z_A) between the charge and the wall being investigated, the scaled distances between the centerline of the wall in question and the adjacent wall (Z_B), the ratio of the distance between the charge and the nearest adjacent wall, to the length of the wall in question (l/L) and the ratio of the height of charge above the floor slab to the height of the wall (h/H). Figure 13 is a typical chart which indicates graphically a method for determining reflection factors as a function of these parameters. In calculating the reflection factors for the side walls, the effects of the reflection of the blast loads off the wall opposite to the one being investigated, have been neglected. After corrections for reflection effects have been made, an equivalent scaled distance of the charge from the wall in question is established. Pressure and impulse loads are then determined from Figure B1 (Reference 10).

APPENDIX C

Primary Fragment Penetration Through Concrete Wall

Some previous data pertaining to a problem (effects of bombs and projectiles striking concrete structures) similar to primary fragment penetration have been obtained (Reference 13). The results of the study covered by this paper, which is based upon empirical and theoretical relationships correlates fairly well with these data.

Figures C1 and C2 are based on these relationships. Figure C1 relates the striking velocity of primary fragments (V_1) with maximum penetration (X_m) for various fragment sizes (m). Once the maximum penetration of a given size fragment is known the fragment residual velocity can be obtained using Figure C2. This plot correlates two ratios, namely, the ratio of the residual velocity to striking velocity (V_2/V_1) and the ratio of wall thickness to maximum penetration (T/X_m). Residual velocity is obtained by multiplying the striking velocity, by the V_2/V_1 ratio.

In order for a fragment to have a residual velocity after penetration through the wall, maximum penetration (X_m) indicated on the previous figure must be greater than the wall thickness (T). The particular charts shown are for a fragment of armor-piercing steel having a general hemispherical shape. For other than armor-piercing fragments a correction factor must be applied (e.g. correction factor for mild steel is 0.70).

In order to provide total protection for personnel and valuable equipment neither spalling nor primary fragment penetration can be tolerated. Figure C3, is a total protection chart for fragments. It relates maximum allowable striking velocity for prevention of spalling and/or penetration, and thickness of the concrete wall for various primary fragment masses.

APPENDIX D

Sandwich-Type Wall Construction

A sandwich type wall is two reinforced concrete walls separated by a compacted sand fill (Figure D1). To evaluate the ultimate capacity of a sandwich type reinforced concrete wall for spalling, punching and flexural capacity, the wall may be reduced to an equivalent standard-type wall by obtaining the attenuated stress wave parameters acting on the front surface of the outside concrete portion. A portion of this reduction is due to the stress and impulse attenuation as the wave passes through the inside concrete wall and sand fill sections of the wall (reduction due to distance). Further stress reduction is due to the change in the magnitude of the stress wave as it passes from one medium to another medium of different density.

Figure D2 is a chart for determination of attenuation of peak pressure in sand and concrete as a function of scaled concrete and sand thicknesses. The solid family of lines refer to concrete, while the broken lines refer to sand. Starting at a point corresponding to the front face of the inside concrete wall a point is located on a solid line corresponding to a given value of pressure (P_r) and scaled thickness of concrete ($T/W^{1/3}$). A vertical downward reading from this point to the point on a broken line corresponding to a known value of scaled thickness of sand ($T_e/W^{1/3}$) is then made. From this point a horizontal reading is made to determine the attenuated peak pressure at the front face of the outside concrete wall. It should be noted that this chart accounts for coupling effects between the sand and concrete.

A similar chart has been developed for the determination of attenuation of scaled impulse per unit area in sand and concrete.

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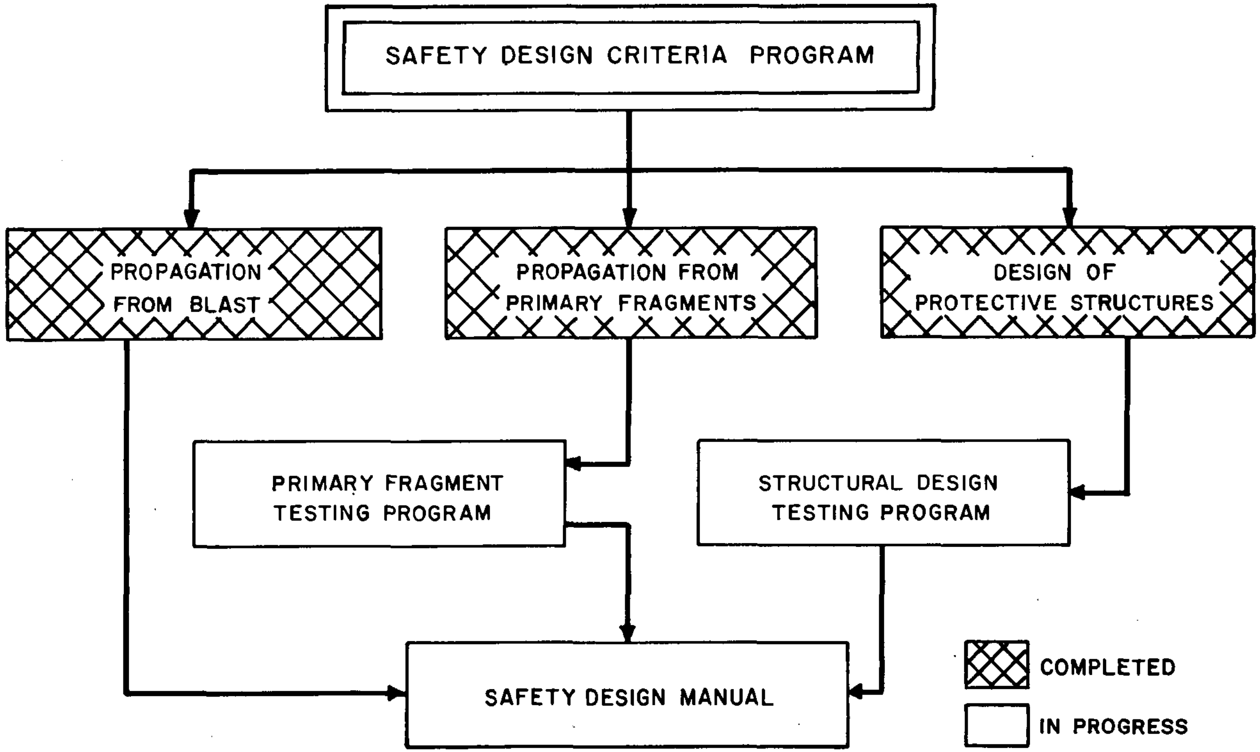

SAFETY DESIGN CRITERIA PROGRAM
PROPAGATION FROM BLAST
PROPAGATION FROM PRIMARY FRAGMENTS
DESIGN OF PROTECTIVE STRUCTURES
PRIMARY FRAGMENT TESTING PROGRAM
STRUCTURAL DESIGN TESTING PROGRAM
SAFETY DESIGN MANUAL
COMPLETED
IN PROGRESS

Figure 1

QUANTITY DISTANCE RELATIONSHIP FOR SYMPATHETIC DETONATION

$$d_m = KW_e^{1/3}, \text{ where } W = F_c\ F_r\ F_e\ F_s\ W$$

d_m = Maximum distance between donor and acceptor charges, at which sympathetic detonation occurs (ft.)

W_e = Weight of a bare, spherical, TNT charge, detonated in free air, which would produce a peak pressure blast output equivalent to that of the actual donor charge (lbs.)

W = Weight of donor explosive charge (lbs.)

K = Blast sensitivity constant (corresponding to minimum peak pressure required at acceptor charge to cause sympathetic detonation)

F_c = Confinement coefficient-Ratio of equivalent bare explosive weight to actual weight of confined explosive (equivalent bare explosive weight is that weight of bare charge which would produce the same peak pressure blast output as the confined donor charge)

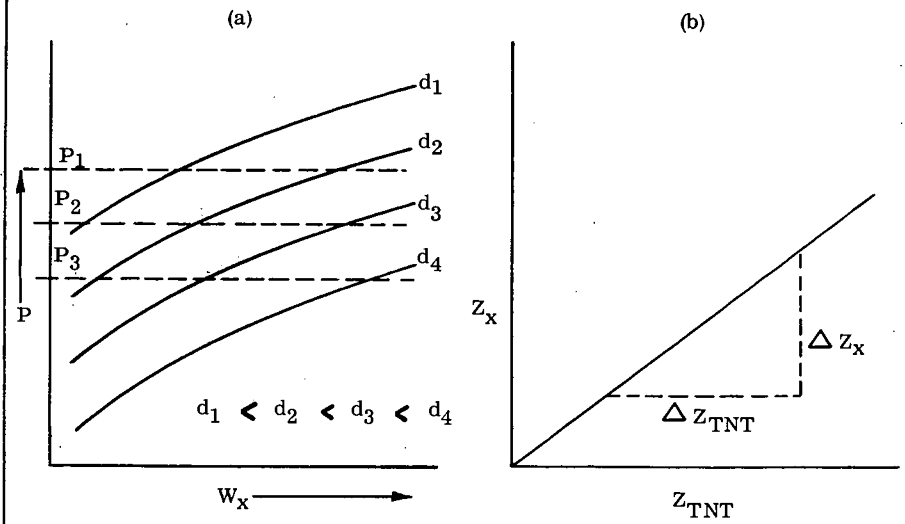
F_r = Reflection coefficient-Ratio of equivalent free-air detonated bare explosive weight to equivalent bare explosive weight of the actual donor charges (equivalent free-air detonated bare explosive weight is that weight of bare explosive which, when detonated in free-air, would produce the same peak pressure blast output as a given donor charge)

F_e = Composition coefficient-Ratio of equivalent free-air detonated bare TNT weight to equivalent free-air detonated bare explosive weight of actual donor charge (equivalent free-air detonated bare TNT weight is that weight of bare TNT which, when detonated in free-air, would produce the same blast output as a given donor charge)

F_s = Shape coefficient-Ratio of peak pressure which would be produced by detonation of equivalent weight $F_c\ F_r\ F_e\ W$ of actual donor shape to peak pressure which would be produced by detonation of same equivalent weight having spherical shape.

Figure 2

DETERMINATION OF EXPLOSIVE COMPOSITION COEFFICIENT, F_e



1. Conduct a series of small scale tests in which different weights (W_x) of bare spherical charges of propellant X are detonated high enough from the ground so that ground reflections are negligible (i.e. F_c, F_s, and F_r each equal 1) and peak pressure (P) measurements are taken at various distances (d) from the detonation source. Plot the data as indicated in Fig. (a).

2. For lines of constant peak pressure obtain the corresponding values of d and W from Fig. (a). Calculate the reduced distance ($d/W_x^{1/3}$) for each point. This should be a constant value for each pressure.

3. For each of the above pressures, obtain the corresponding reduced distance from the Kirkwood-Brinkley relationship for bare, spherical TNT charges detonated in free air (Ref 5).

4. Plot propellant X reduced distance (Z_x) against TNT reduced distance (Z_{TNT}) for each pressure as shown in Fig. (b). These points should fall along a straight line passing through the origin. The slope of this line equals $F_e^{1/3}$, or

$$F_e = \left[\frac{\Delta Z_x}{\Delta Z_{TNT}}\right]^3 = \left[\frac{d/W_x^{1/3}}{d/W_{TNT}^{1/3}}\right]^3 = \frac{W_{TNT}}{W_x}$$

Figure 3

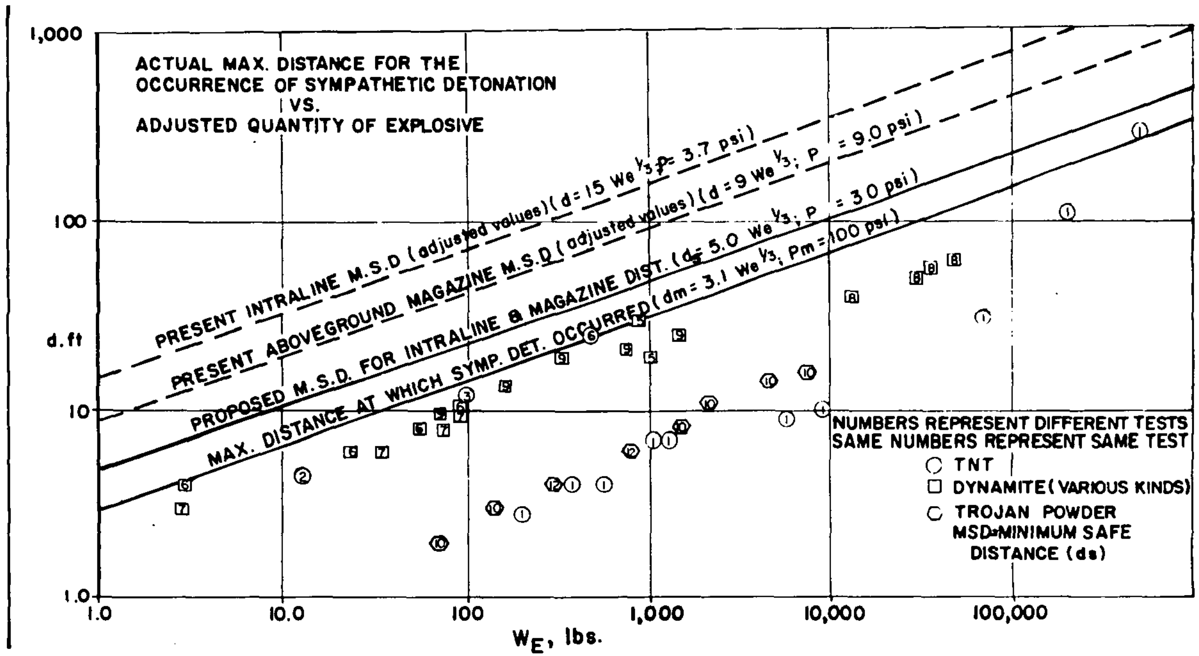

ACTUAL MAX. DISTANCE FOR THE
OCCURRENCE OF SYMPATHETIC DETONATION
VS.
ADJUSTED QUANTITY OF EXPLOSIVE
PRESENT INTRALINE M.S.D (adjusted values)(d = 15 We 1/3; P = 3.7 psi)
PRESENT ABOVEGROUND MAGAZINE M.S.D (adjusted values)(d = 9 We 1/3; P = 9.0 psi)
PROPOSED M.S.D. FOR INTRALINE & MAGAZINE DIST. (ds = 5.0 We 1/3; P = 30 psi)
MAX. DISTANCE AT WHICH SYMP. DET. OCCURRED (dm = 3.1 We 1/3; Pm = 100 psi)
d.ft
1,000
100
10
1.0
1.0
10.0
100
1,000
10,000
100,000
WE, lbs.
NUMBERS REPRESENT DIFFERENT TESTS
SAME NUMBERS REPRESENT SAME TEST
TNT
DYNAMITE (VARIOUS KINDS)
TROJAN POWDER
MSD=MINIMUM SAFE
DISTANCE (ds)

Figure 4

Effect of Various Explosive Weight Correction Factors on Minimum Safe Distance

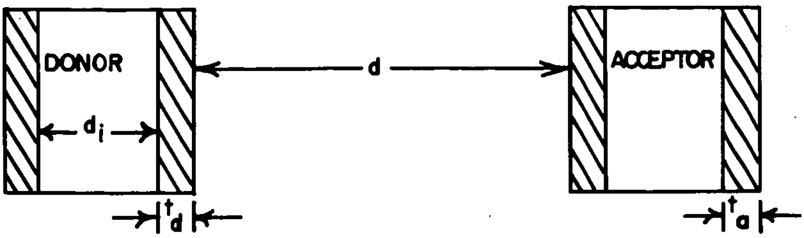
Assume 10,000 lbs of donor explosive of cylindrical over all shape (F_s=1.25)

Explosive	Reflection Factor / Explosive/ Total wt. ratio, C.	(Assumed F_r=1.5) C=0.9 F_c=1.17	C=0.7 F_c=1.04	C=0.5 F_c=0.6	(Assumed F_r=1.8) C=0.9 F_c=1.17	C=0.7 F_c=1.04	C=0.5 F_c=0.6	(Assumed F_r=2.0) C=0.9 F_c=1.17	C=0.7 F_c=1.04	C=0.5 F_c=0.6
TNT	W_e	24,000	21,500	12,500	29,000	25,500	15,000	32,000	28,500	16,300
(F_e=1.0)	d_s	144.0	139.0	116.0	153.0	146.0	122.0	158.0	153.0	127.0
Explosive X	W_e	27,000	24,000	14,000	32,200	28,500	17,000	36,000	31,800	18,500
(F_e=1.13)	d_s	150.0	144.0	120.0	158.0	153.0	129.0	165.0	158.0	132.0
Explosive Y	W_e	28,800	25,600	14,900	34,600	30,500	17,800	37,100	34,000	19,500
(F_e=1.19)	d_s	153.0	147.0	123.0	163.0	157.0	131.0	169.0	162.0	134.0
Explosive Z	W_e	30,500	27,500	16,000	37,000	32,500	19,100	40,600	36,200	20,800
(F_e=1.27)	d_s	157.0	151.0	126.0	169.0	159.0	133.0	172.0	165.0	138.0

NOTE: According to present quantity-distance regulations, d_s for the assumed 10,000 pound donor explosive charge would be 400 feet, regardless of the widely varying conditions indicated above.

Figure 5

SCHEMATIC REPRESENTATION OF DONOR–ACCEPTOR RELATIONSHIPS GOVERNING PROPAGATION BY FRAGMENT IMPACT



$V_o = f\,(E')(E)/C)$ - - - - - - - - - - - - (1)

V_o = initial fragment velocity

E' = explosive output constant

E/C = explosives / casing weight ratio

$N_x = f\,(B)(C)(t_d)(d_i)(m)$ - - - - - - - (2)

N_x = number of fragments greater than mass (m)

m = mass of fragment produced by donor detonation

B = constant depending on donor explosive and casing material

C = donor casing weight

t_d = donor casing thickness

d_i = inside diameter of donor casing

$m_{max} = f\,(B)(C)(t_d)(d_i)$ - - - - - - - - (2a)

m_{max} = mass of largest fragment produced by donor detonation.

$V_b = f\,(K_f)(t_a)(m)$ - - - - - - - - - - - (3)

V_b = boundary velocity or fragment striking velocity of mass, m, below which high order detonation of the acceptor will not occur.

K_f = explosive sensitivty constant

t_a = acceptor casing thickness

$V_{b\,min} = f\,(K_f)(t_a)(m_{max})$ - - - - - - - - - (3a)

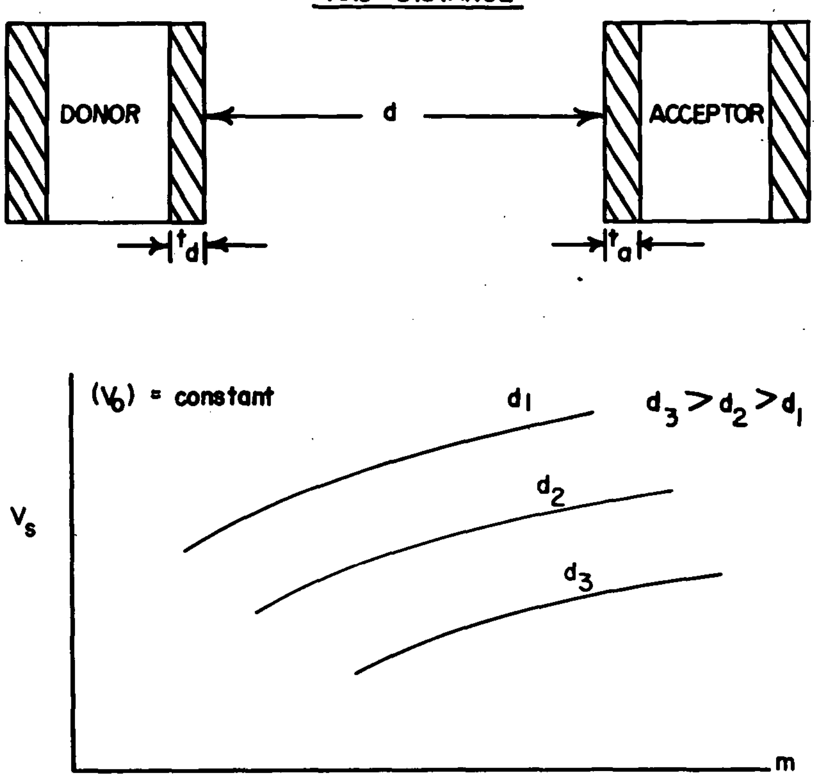
$V_{b\,min}$ = minimum boundary velocity required for detonation of given acceptor by fragment from given donor.

IF $\dfrac{V_o}{V_{b\ min}} < 1$: detonation by fragment impact will not occur.

IF $\dfrac{V_o}{V_{b\ min}} \geq 1$: possibility of detonation by fragment impact exists.

Figure 6

STRIKING VELOCITY OF A FRAGMENT AS A FUNCTION OF FRAGMENT MASS AND DISTANCE



$$d = f\,(k)(V_o/V_s)(m) \qquad (4)$$

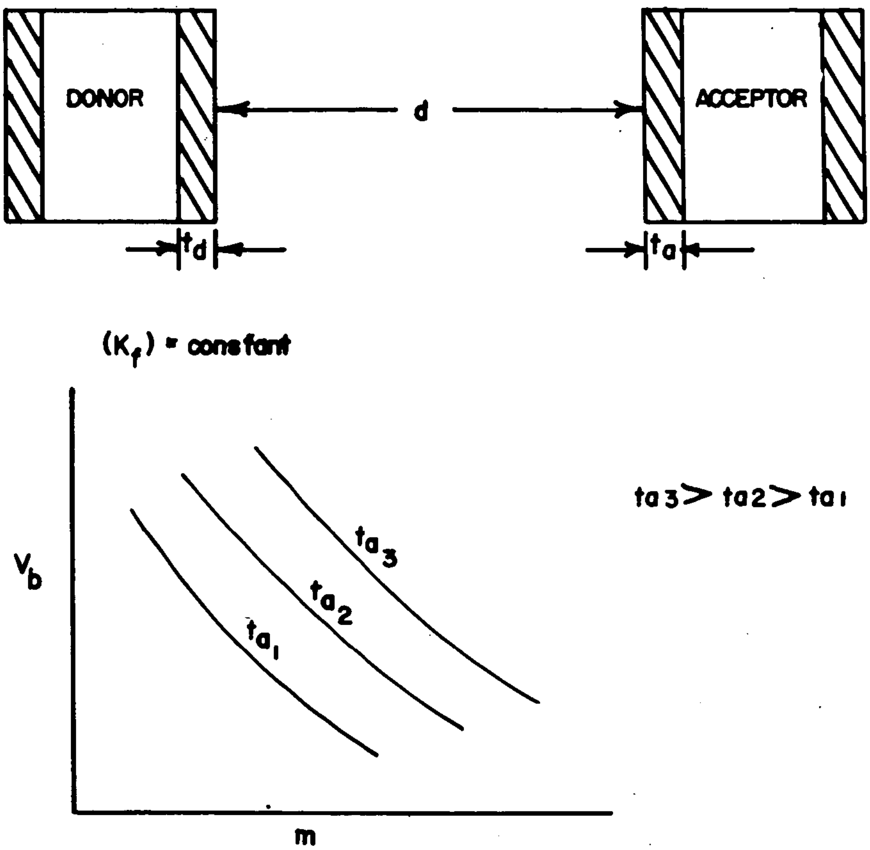
d = distance from the donor charge.

k = constant depending on fragment size, shape, air density and drag coefficient.

V_s = striking velocity of fragment at a distance. d

Figure 7

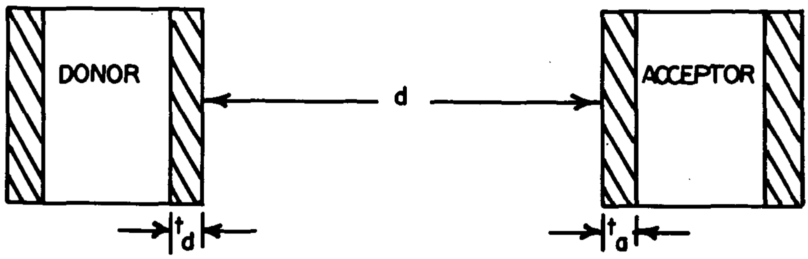
BOUNDARY VELOCITY OF A FRAGMENT AS A FUNCTION OF FRAGMENT MASS AND ACCEPTOR SHIELDING

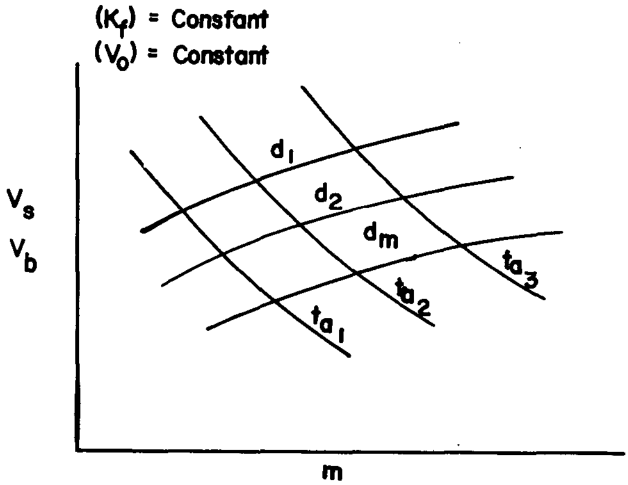


$$V_b = f(K_f)(t_a)(m) \quad \text{.........................} \quad (3)$$

Figure 8

MINIMUM EFFECTIVE FRAGMENT MASS AND CORRESPONDING VELOCITY AS A FUNCTION OF DISTANCE AND SHIELDING



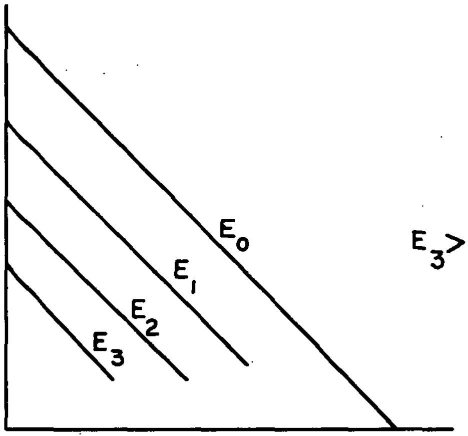


$d_m = f\,(k)\,(V_0/V_b)_{min}(M_{max})$ ---------------------- (4_a)

WHERE d_m = maximum distance from given donor charge at which detonation of given acceptor is possible.

Figure 9

PROBABILITY OF DETONATION OCCURRENCE AS A FUNCTION OF DISTANCE AND SHIELDING



$E_3 > E_2 > E_1$

E_0 – Zero probability curve

$$P/A = f(N_x)(d)(g) \text{ - - - - - - - - - - (5)}$$

$$E = f(P) \text{ - - - - - - - - - - - - - - (5a)}$$

P/A = Probable number of effective hits per unit area.

(N_x) = Total number of effective fragments.

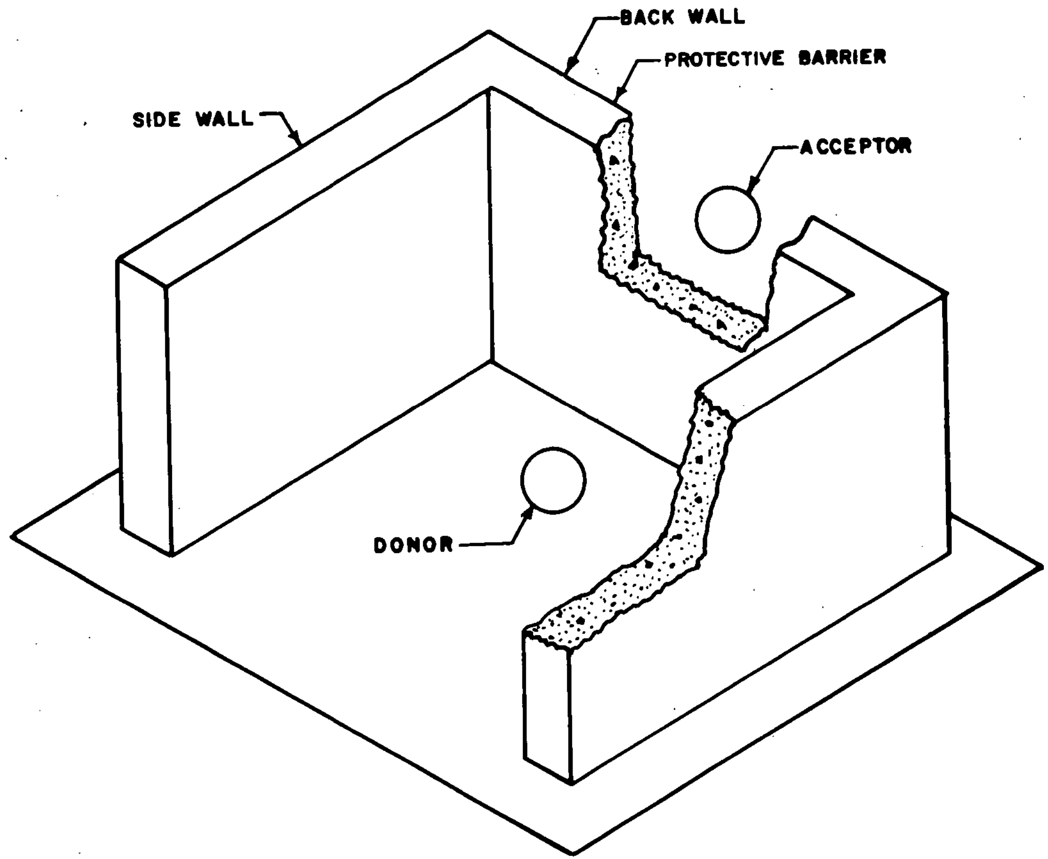
(g) = Factor governing the distribution of fragments.

(D) = Distance between donor and acceptor charge.

(E) = Probability of high order detonation occurrence in the acceptor.

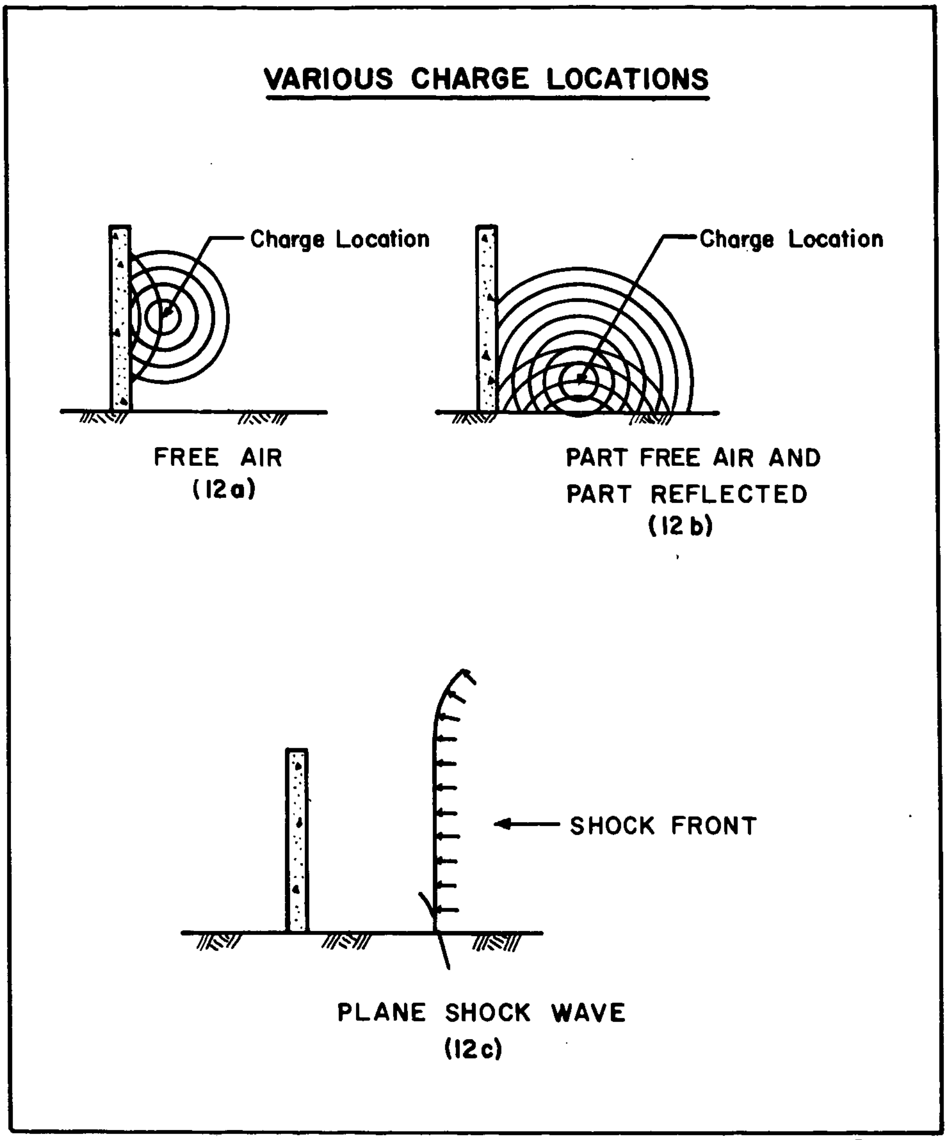
(A) = Presented area of the acceptor

Figure 10



ISOMETRIC OF WALL CUBICLE

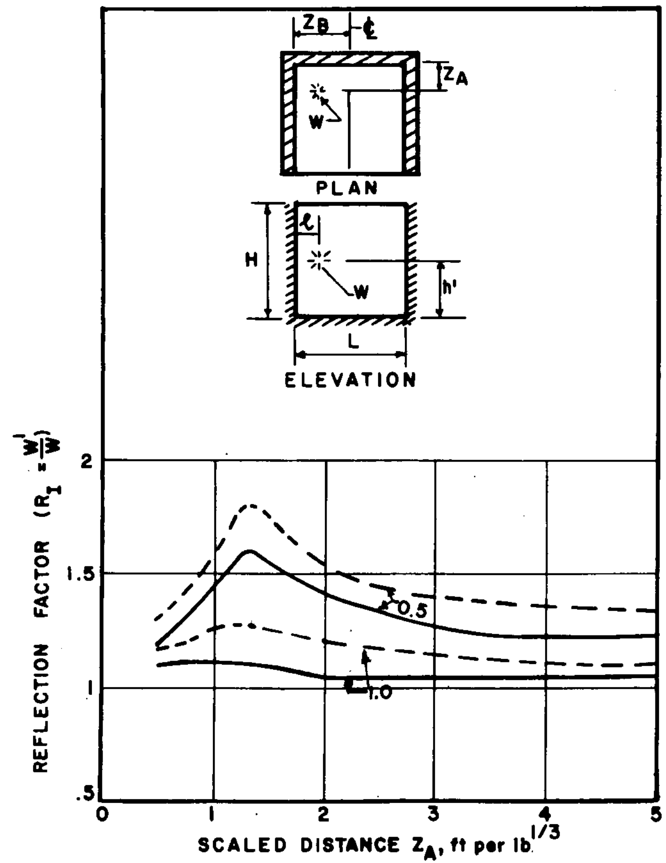
Figure 11



Ref. 4

Figure 12

REFLECTION FACTORS IN A CUBICLE TYPE STRUCTURE
FOR WALL FIXED AT THE BASE AND TWO SIDES

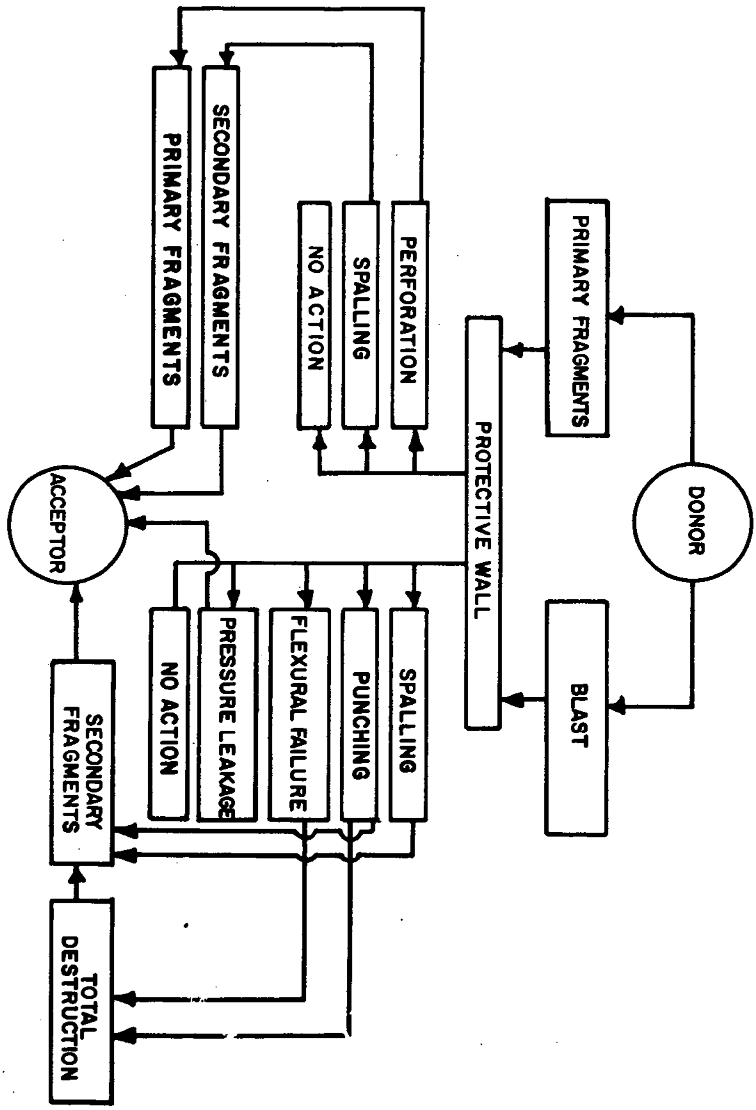


LOCATION OF CHARGE
—— $0.5 \times H = h'$
– – – $0.25 \times H = h'$

NOTE: NUMBERS ADJACENT TO CURVES INDICATE VALUES OF Z_B/Z_A

Figure 13

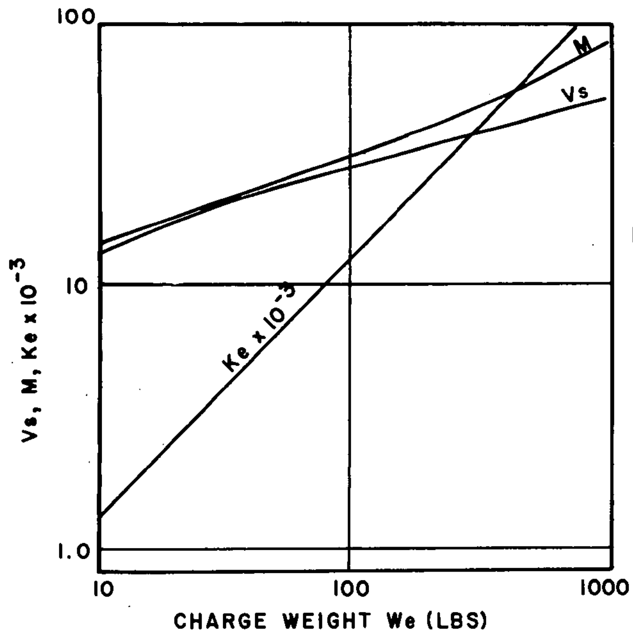
Ref. 4



DESIGN OF PROTECTIVE STRUCTURES

Figure 14

CHARGE WEIGHT VS VELOCITY, MASS, KINETIC ENERGY OF THE SPALL
(FOR T = 1 FOOT)
(Z = 0.5)



V_s - VELOCITY OF THE SPALL (FT/SEC)

M - MASS OF THE SPALL $\left(\frac{\text{LBS SEC}^2}{\text{FT}}\right)$

Ke - KINETIC ENERGY OF THE SPALL (FT LBS)

T - THICKNESS OF THE WALL

Z - SCALED DISTANCE (FT/LB$^{1/3}$)

We - CHARGE WEIGHT (LBS)

Ref. 4

Figure 15

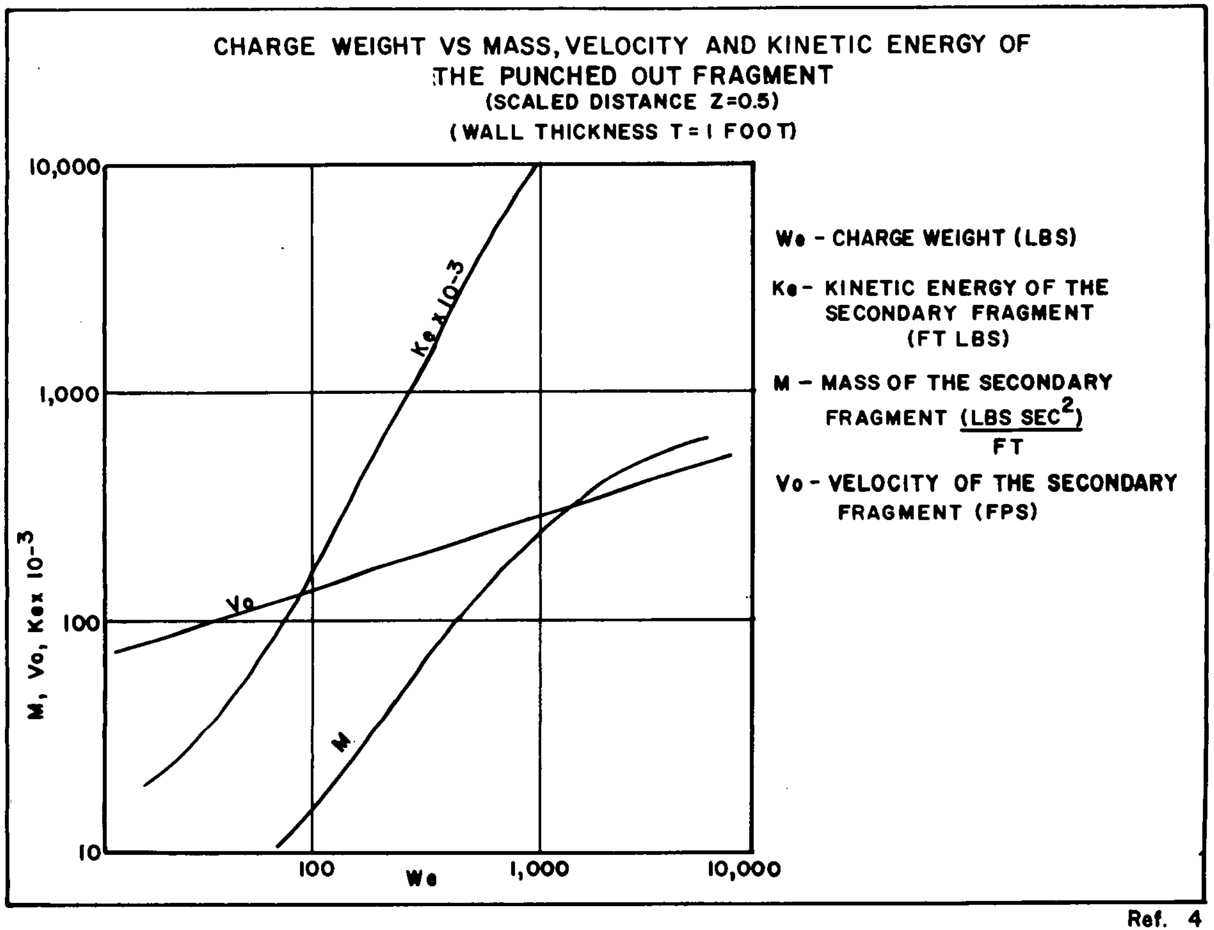
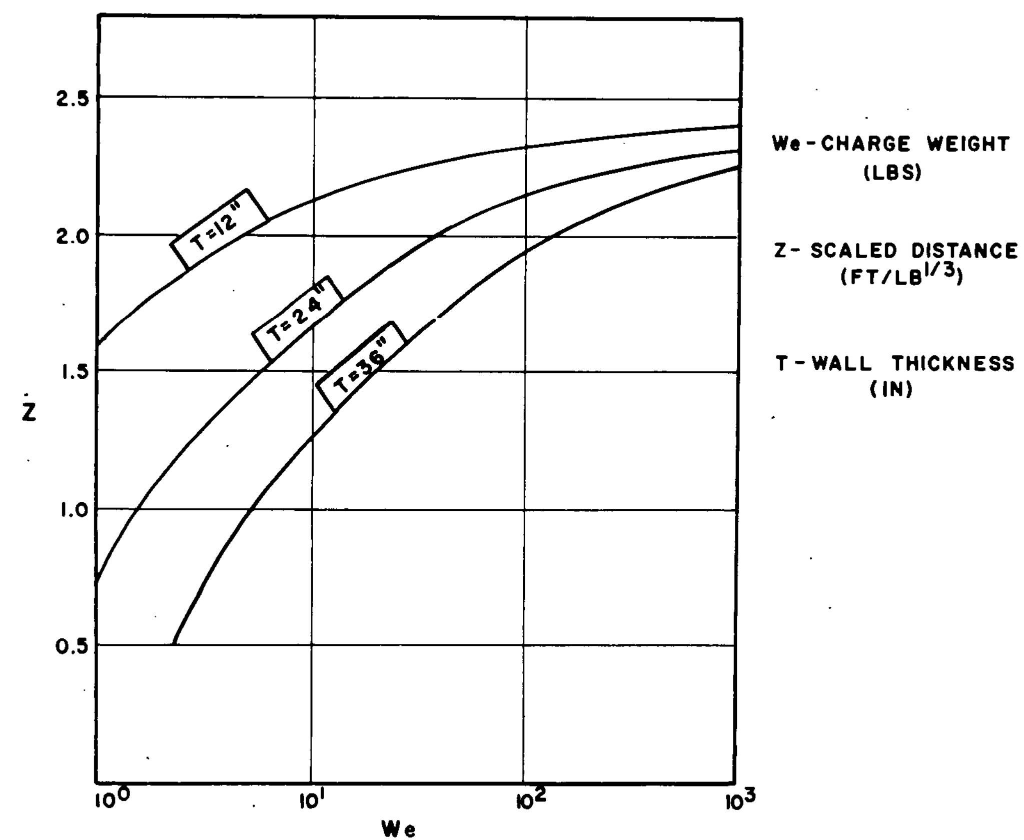

CHARGE WEIGHT VS MASS, VELOCITY AND KINETIC ENERGY OF
THE PUNCHED OUT FRAGMENT
(SCALED DISTANCE Z=0.5)
(WALL THICKNESS T=1 FOOT)
10,000
1,000
100
10
M, Vo, Ke x 10-3
100
1,000
10,000
We
Ke x 10-3
Vo
M
We - CHARGE WEIGHT (LBS)
Ke - KINETIC ENERGY OF THE SECONDARY FRAGMENT (FT LBS)
M - MASS OF THE SECONDARY FRAGMENT (LBS SEC2) / FT
Vo - VELOCITY OF THE SECONDARY FRAGMENT (FPS)
Ref. 4

Figure 16

TOTAL PROTECTION CHART FOR SPALLING DUE TO BLAST



Ref. 4

Figure 17

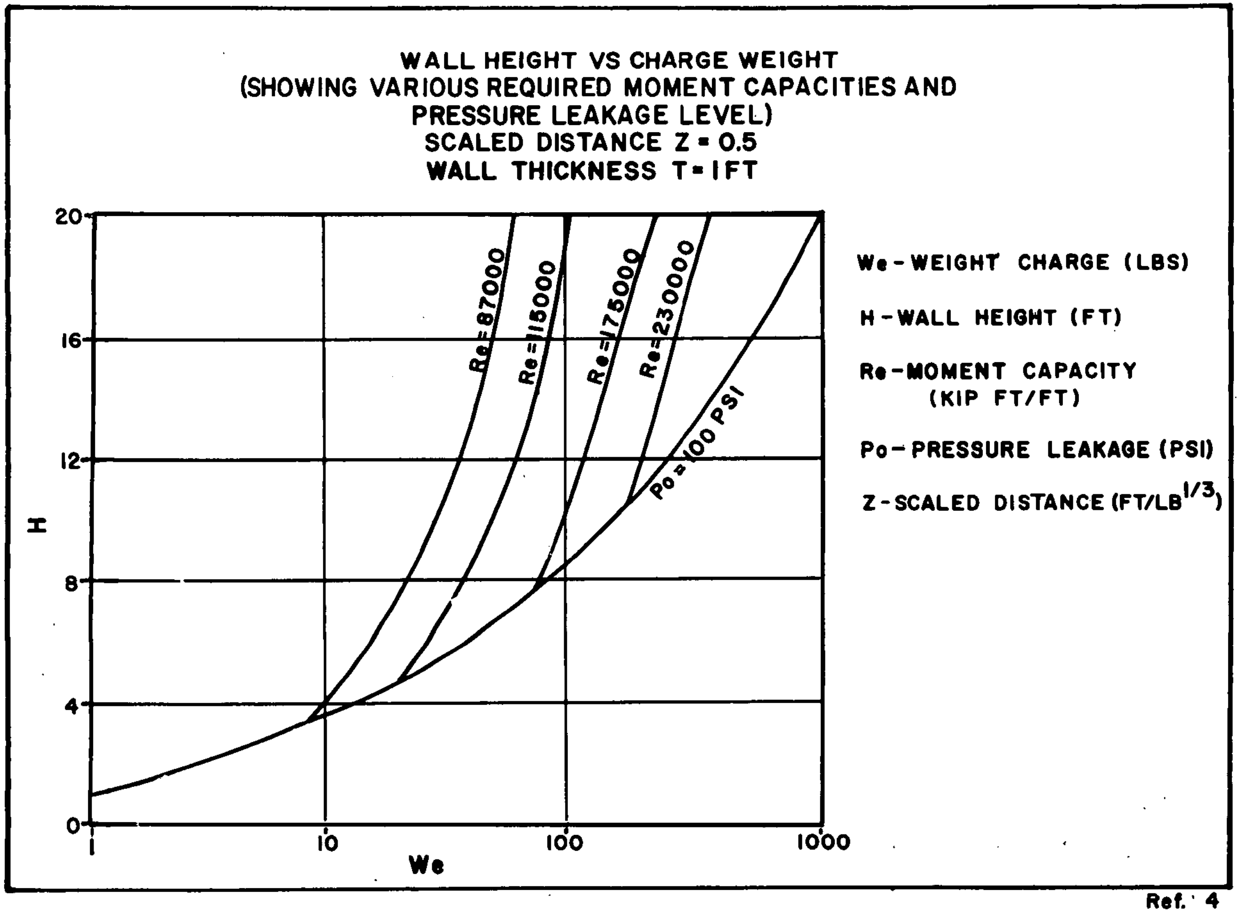
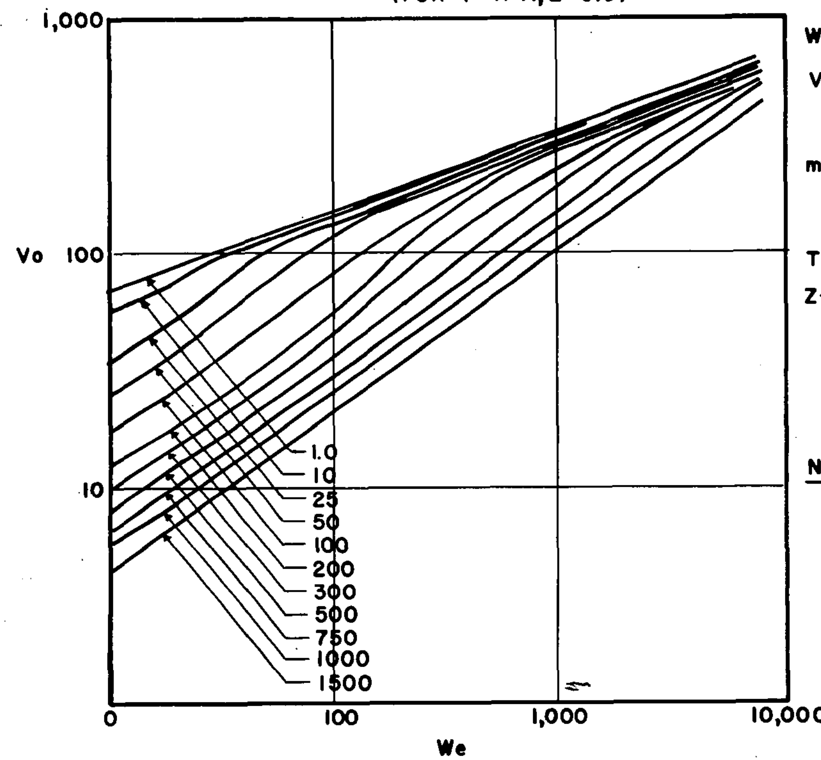

WALL HEIGHT VS CHARGE WEIGHT
(SHOWING VARIOUS REQUIRED MOMENT CAPACITIES AND
PRESSURE LEAKAGE LEVEL)
SCALED DISTANCE Z = 0.5
WALL THICKNESS T = 1 FT
H
20
16
12
8
4
0
1
10
100
1000
We
Re=87000
Re=115000
Re=175000
Re=230000
Po=100 PSI
We - WEIGHT CHARGE (LBS)
H - WALL HEIGHT (FT)
Re - MOMENT CAPACITY
(KIP FT/FT)
Po - PRESSURE LEAKAGE (PSI)
Z - SCALED DISTANCE (FT/LB^1/3)
Ref. 4

Figure 18

TOTAL DESTRUCTION CHART, CHARGE WEIGHT VS VELOCITY OF SECONDARY FRAGMENTS

(FOR T-1FT., Z=0.5)



We - CHARGE WEIGHT (LBS)

Vo - VELOCITY OF THE SECONDARY FRAGMENTS (FPS)

m - MASS OF THE SECONDARY FRAGMENTS $\frac{(LBS\ SEC^2)}{FT}$

T - THICKNESS OF THE WALL (FT)

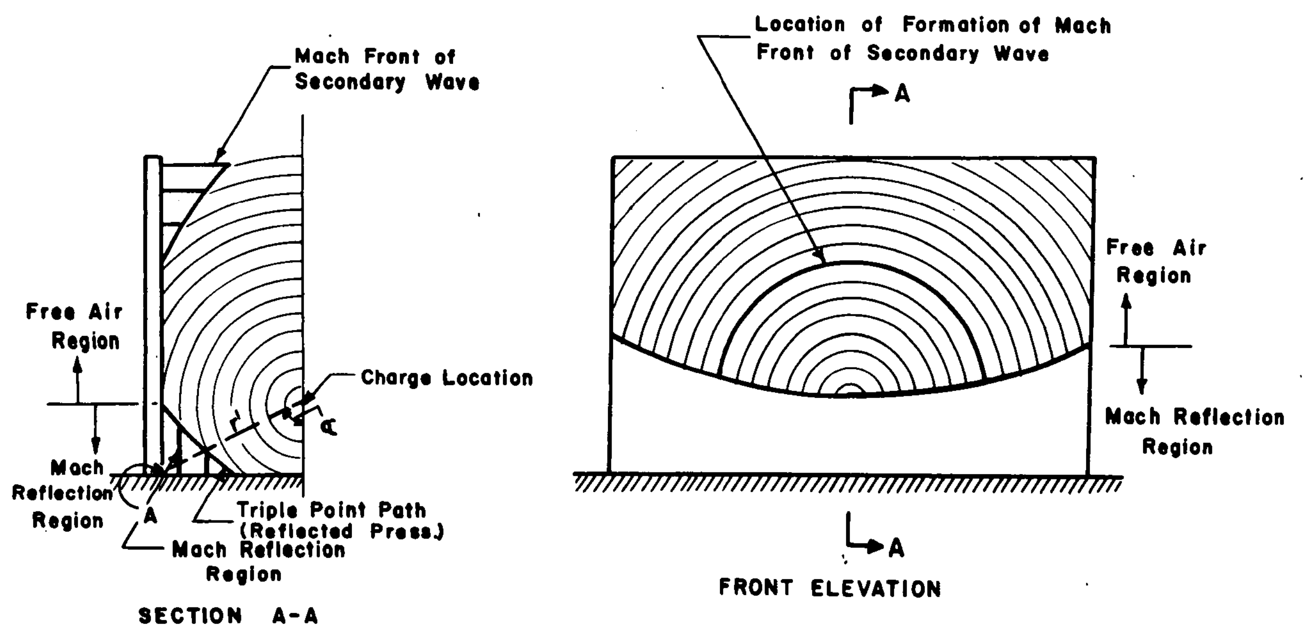
Z - SCALED DISTANCE ($FT/LB^{1/3}$)

NOTE: The numbers adjacent to the lines indicate values of the mass - $\frac{lb\text{-}sec^2}{ft}$

Ref. 4

Figure 19

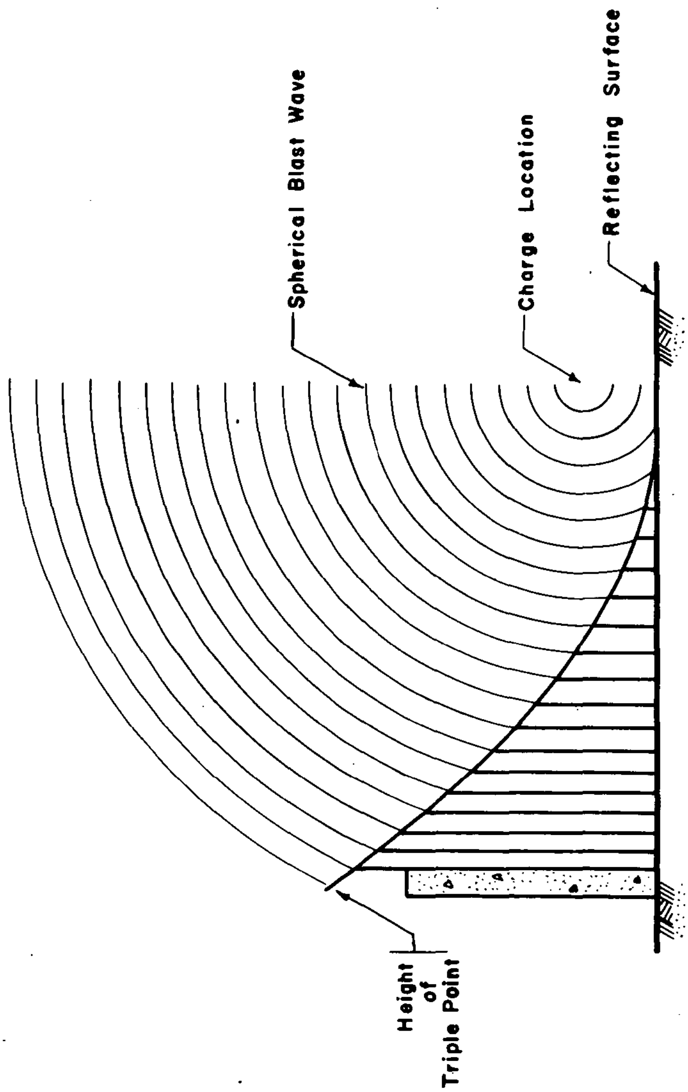
WALL SUBJECTED TO FREE AIR AND REFLECTED PRESSURES



Ref. 4

Figure A1

WALLS SUBJECTED TO PLANE SHOCK WAVES



Ref. 4

Figure A2

PEAK PRESSURE AND SCALED IMPULSE vs SCALED DISTANCE

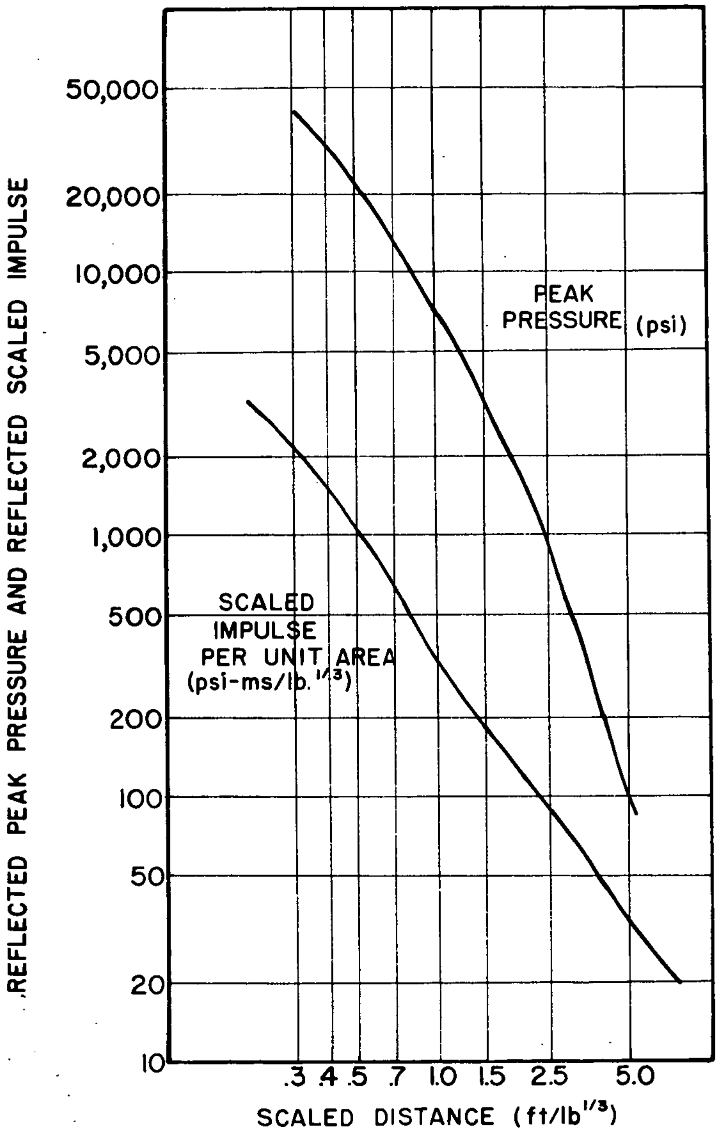
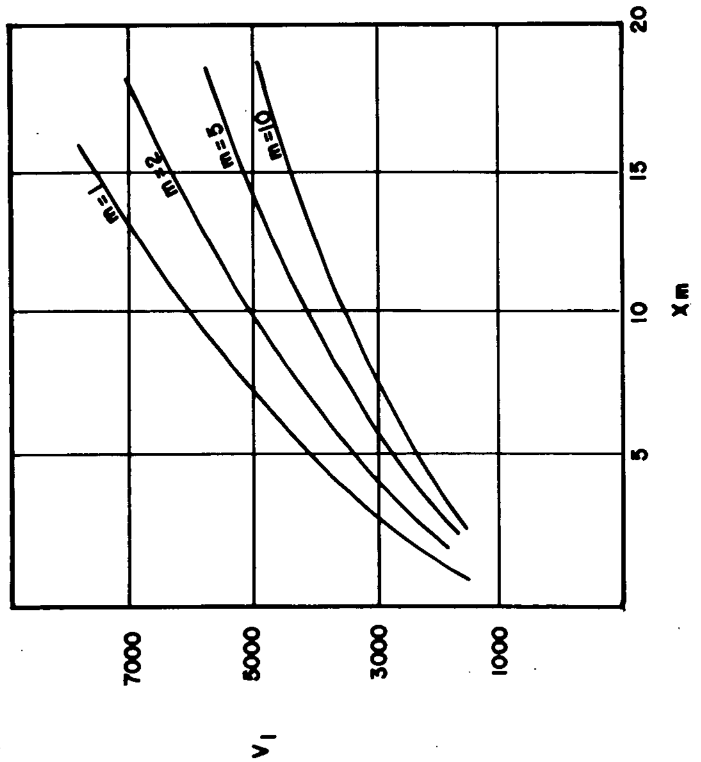


Figure BI

Ref. 4

PRIMARY FRAGMENT STRIKING VELOCITY
VS
MAXIMUM PENETRATION



V_1 - STRIKING VELOCITY OF PRIMARY FRAGMENT (FPS)

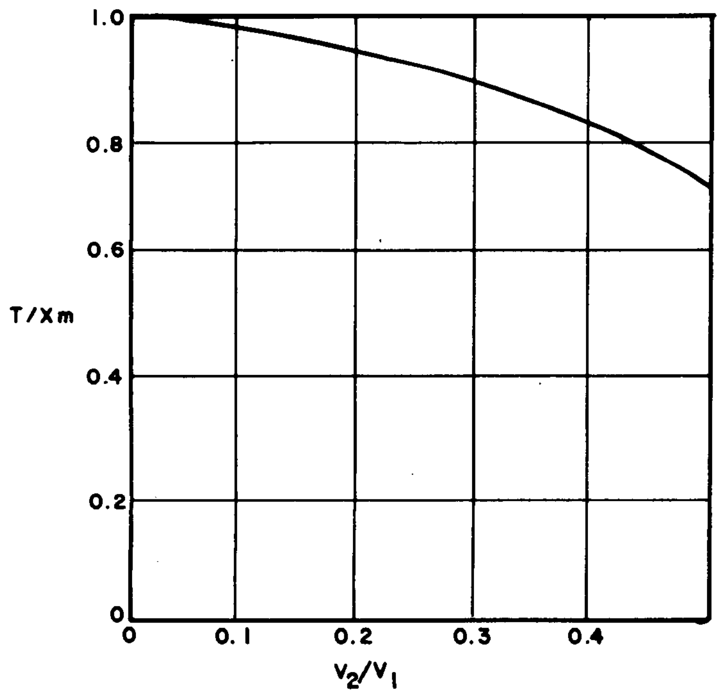
Xm - MAXIMUM FRAGMENT PENETRATION (IN)

m - FRAGMENT WEIGHT (OZ)

Figure C1

Ref. 4

RATIO OF RESIDUAL VELOCITY TO
STRIKING VELOCITY
VS
RATIO OF WALL THICKNESS TO FRAGMENT
MAXIMUM PENETRATION



V_1 - STRIKING VELOCITY OF PRIMARY FRAGMENTS (FPS)

V_2 - RESIDUAL VELOCITY OF PRIMARY FRAGMENTS (FPS)

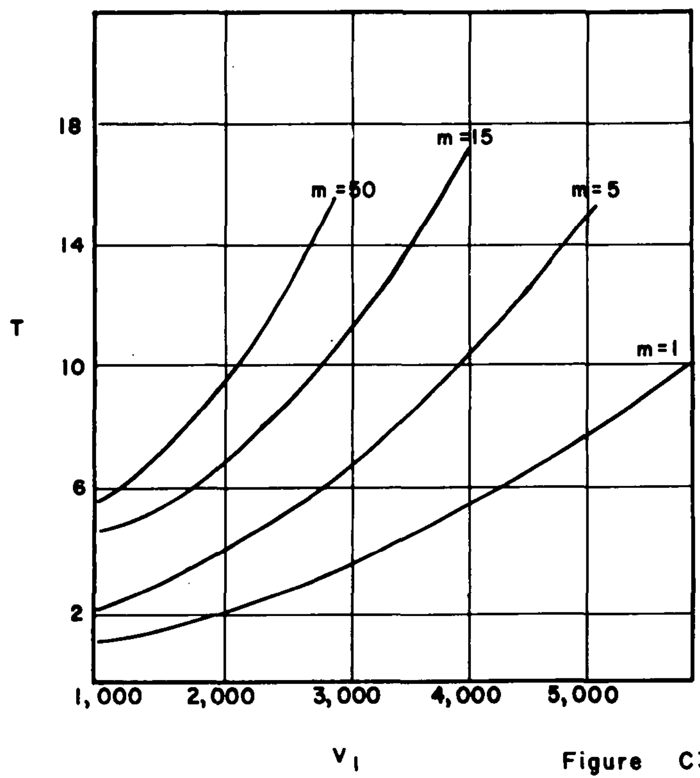
T - WALL THICKNESS (IN)

Xm - MAXIMUM FRAGMENT PENETRATION (IN)

Ref. 4

Figure C2

VELOCITY OF PRIMARY FRAGMENTS VS THICKNESS OF THE WALL



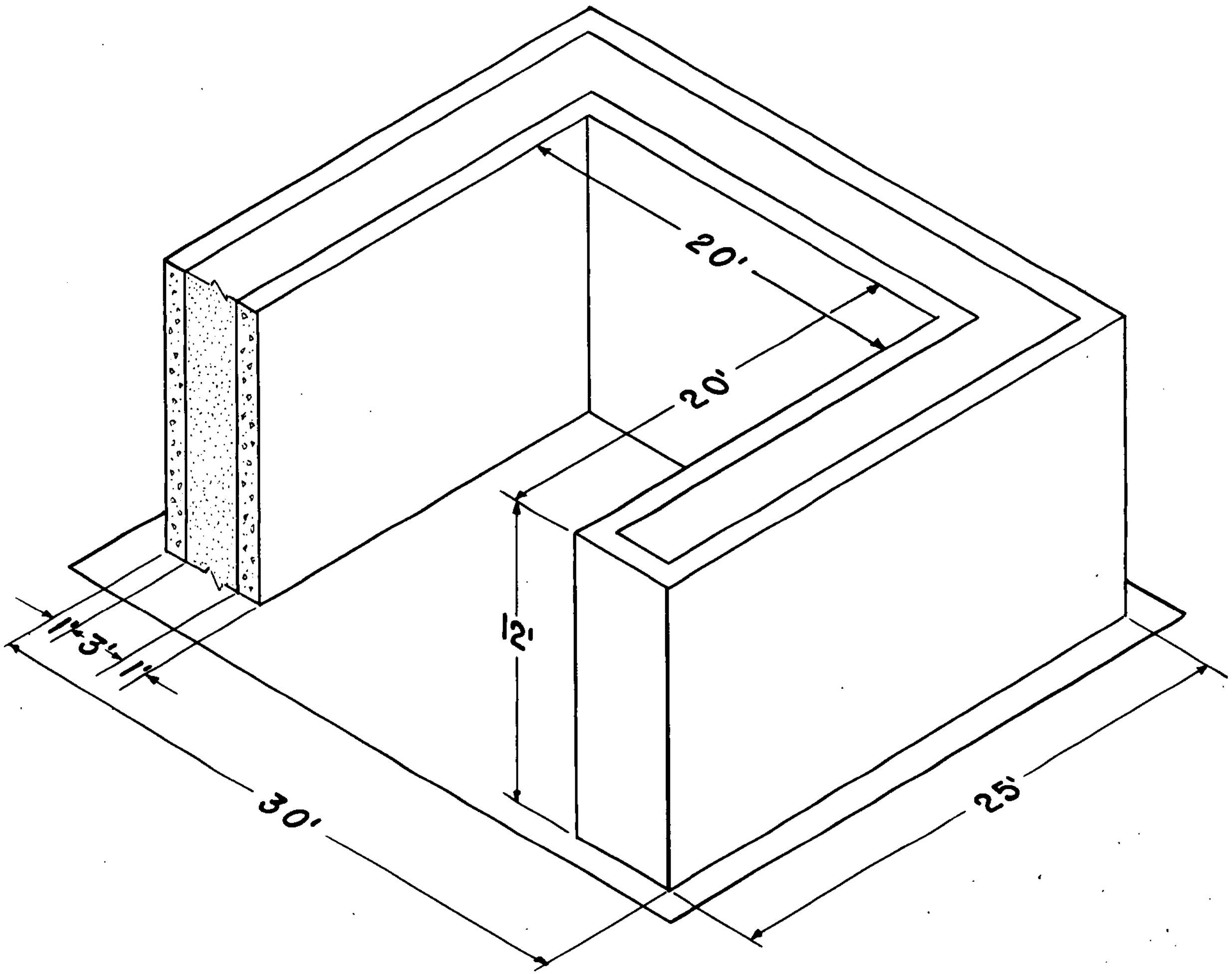
V_I - VELOCITY OF PRIMARY FRAGMENTS (FPS)

T - WALL THICKNESS (IN)

m - WEIGHT OF PRIMARY FRAGMENTS (OZ)

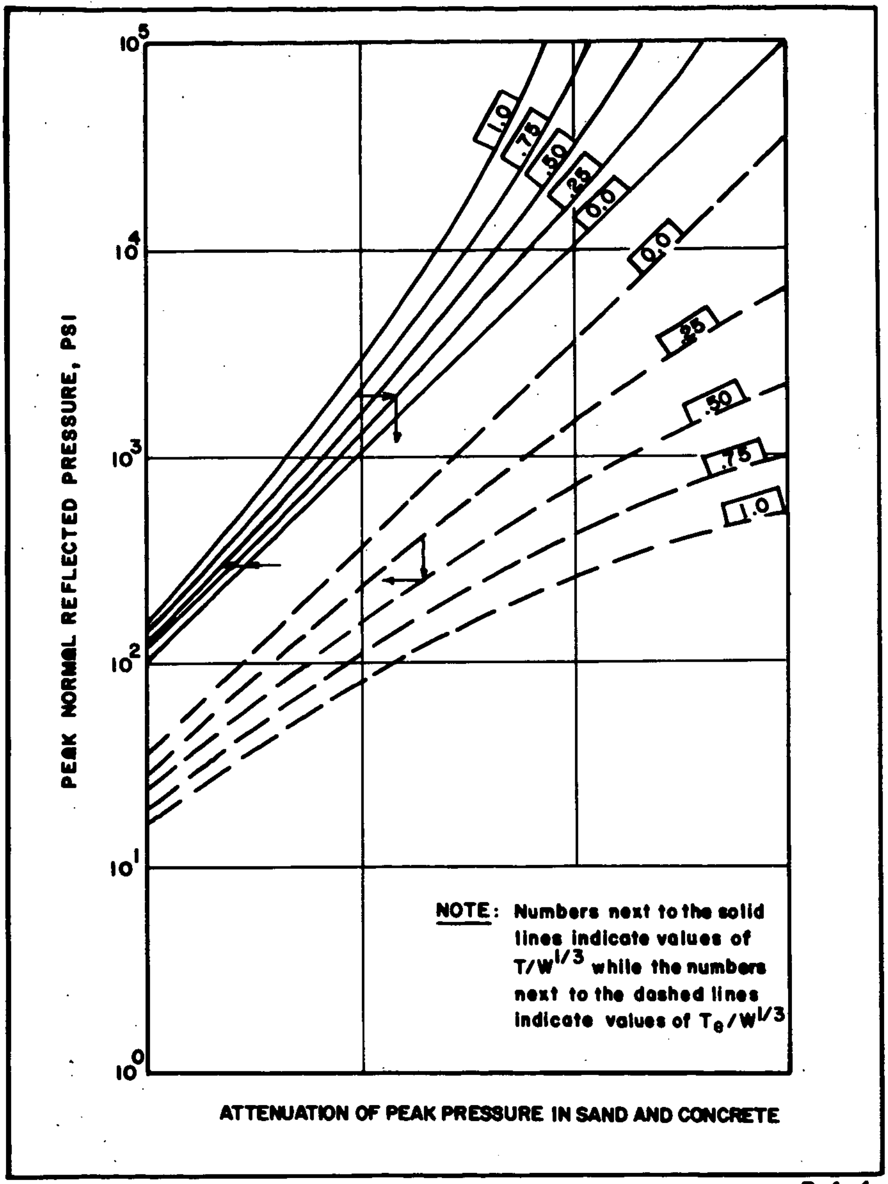
Figure C3

Ref. 4



ISOMETRIC OF SANDWICH WALL CUBICLE

Figure D1



Ref. 4

Figure D2